INOVE: a testbench for the analysis and control of automotive vertical dynamics

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INOVE: A TESTBENCH FOR THE ANALYSIS AND CONTROL OF AUTOMOTIVE VERTICAL DYNAMICS

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ABSTRACT

This paper introduces the INOVE testbed, a novel experimental platform designed for the study of vertical dynamics in road vehicles. A complete description of the physical characteristics and capabilities of the system is presented. Also we show some of the current/possible applications of this system, regarding significant topics as: modelling, observation fault detection and control.

Keywords: Vehicle dynamics, Modelling, System identification, Observers, Control, FTC, FDI, Automotive suspension.

1. INTRODUCTION

Among research institutions and vehicle manufacturers, the current government politics and society concerns regarding road safety are a major matter of study. According to the report of the World Health Organization (WHO) on road safety of 2013 [1], the number of deaths due to road accidents is currently decreasing but, it is noteworthy that around the world still almost 3,400 people die each day. Just in Europe, each year more than 2 million people are injured, of which about 40% need a stay in hospital, and almost 90,000 people decease in road related accidents. To reduce those statistics the WHO has established 5 pillars towards road safety, in which to achieve "Safer vehicles" is one of them. From the use of new materials and structures in the vehicle body to the implementation of control systems that help the driver in critical situations, different approaches have been developed to achieve this objective.

The INOVE testbed focuses on the improvement of vehicle control systems, especially those who manage the way a vehicle behaves dynamically. This kind of controllers can be evaluated in 6 degrees-of-freedom: translations in the longitudinal, lateral and vertical axes, as well as the rotation around the roll, pitch and yaw axes. These movements can be controlled using several types of actuators, as: active or semi-active dampers, active steering, independent braking, active differentials, etc. Among this variety of actuators, the suspension system is the only one that can influence the passenger comfort as well as the car road handling. It is then of huge interest in global chassis control technology.

The INOVE test rig aims to study how the suspension system modifies the vehicle vertical dynamics, especially when using semi-active dampers. Even though, the main objective of the INOVE testbed focuses on the effects of semi-active suspension systems, due to its characteristics, in terms of sensors and actuators, this platform is not limited to control but also can be used in other applications like modelling, observation, and estimation [2].

This work is divided as follows: Section 2 introduces the INOVE test bench giving a detailed description of the system and the available equipment (sensors and actuators). In section 3, some implemented and possible applications developed in this experimental platform are presented, such applications are divided in three topics: Modelling, Observation and Estimation, and Control. Finally section 4 presents future work and conclusions.

2. INOVE TESTBED

In this section the INOVE test bench is described in detail, regarding its components and its operational characteristics, then some remarks of the use of the platform are discussed.

2.1 System description

This experimental platform is composed of 3 main parts: A) Host PC, B) Target PC, and C) Process. The system is illustrated in Fig. 1.

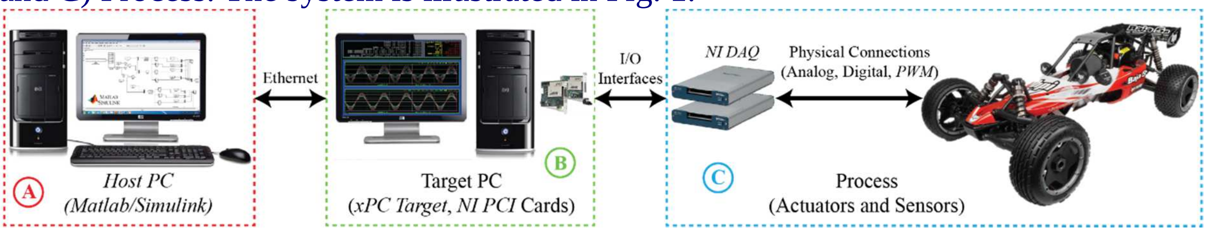

Fig. 1 Schematic of INOVE experimental platform

- Host PC: The control interface is hosted in this computer. In this interface is where the user sets the initialization parameters, configures the desired road profile, implements the suspension control algorithms, and records the acquired data. This interface is developed using Matlab/Simulink™.
- Target PC: In this computer, a RT operating system (xPC Target™) is running. In this PC the control algorithm is compiled and executed at a sampling time of 200 Hz.
- Process: The process includes sensors, actuators, and the scaled vehicle.

In the Process the principal piece is a 1:5-scaled baja style racing car, which represents a full vehicle including wheels, engine, steering, breaking system, and the key element a SA suspension system. In fact, this platform is dedicated to study the vertical behaviour of the car, it is why neither the steering nor breaking systems will be used.

The SA suspension system involves four Fludicon™ Electro-Rheological (ER) dampers which have a force range of ±50 N, Fig. 2. This dampers are adjusted using a manipulation voltage between 0 and 5 kV, generated thanks to the amplifiers modules CarCon2™. The control input for the CarCon2 modules is a PWM signal at 25 kHz, these amplifiers proportionally transform into voltage the duty-cycle of the received PWM signal.

Below each wheel lies an OMRON™ linear servomotor that mimics the desired road profile. The servomotors have a bandwidth of 0-20 Hz with a maximum velocity of 1.5

m/s. Each motor has its own servo-driver and is operated from the Host PC by sending the desired road profile through a DAQ.

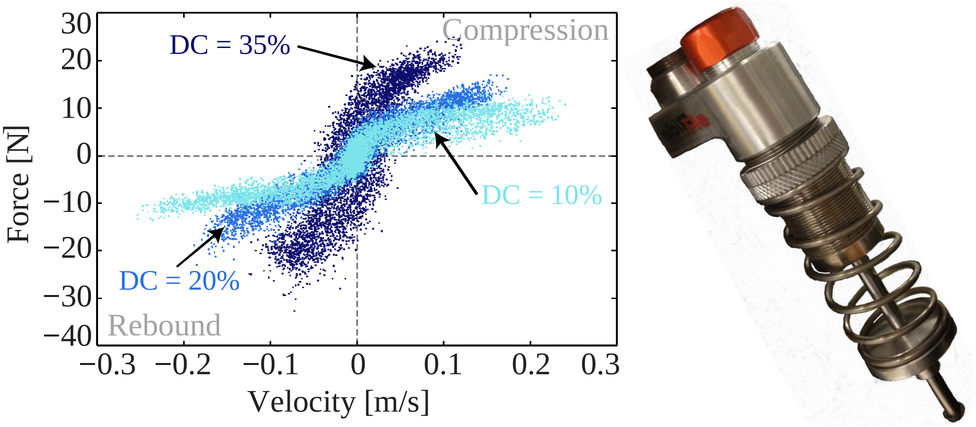

Fig. 2 ER damper (right) and its force characteristic diagram (left)

To capture the behaviour of the vehicle, this platform is equipped with a wide variety of sensors. To measure the vertical accelerations of the unsprung masses ($\ddot{z}_{us}$) 4 Texense™ 1-axis capacitive accelerometers were used. The deflection of the suspensions (z_{def}) were measured using 4 Gefran™ resistive linear displacement sensors and the other 4 to measure road profile (z_r). Also 4 Micro-Epsilon™ draw-wire displacement sensors were used to measure the unsprung masses displacements (z_{us}).

Since the main idea of this platform is to evaluate the dynamical behaviour of the full vehicle, the system is equipped with a SBG™ MEMS based Attitude and Heading Reference System (AHRS) which measures the movements of the sprung mass; 3 accelerations: longitudinal ($\ddot{x}$), lateral ($\ddot{y}$) and vertical ($\ddot{z}$), and 3 angular velocities: pitch rate ($\dot{\phi}$), roll rate ($\dot{\theta}$), and yaw rate ($\dot{\psi}$).

To analyse the force changes of the ER dampers, it possess 4 force sensors. Also other 4 sensors were used to measure tire forces.

The data acquisition and signal outputs for all the sensors and actuators were done through 2 X series NI DAQs.

2.2 Operation remarks

Since this system is specially designed to evaluate the vertical dynamics of a vehicle, and the influence of the suspension system in them, there are some considerations, regarding its operation that need to be taken into account when operating the experimental platform.

Remark 1. The only input of the system is the movement of the lineal servomotors, which represent the desired road profile in each of the wheels.

Remark 2. To operate the semi-active dampers, the control input should be the percentage of duty cycle for the PWM command signal.

Remark 3. Due to the physical characteristics of the system, only the vertical dynamics, pitch, roll and vertical bounce, can be induced in the system. Even if the sensors detect other dynamics (longitudinal or lateral), these movements should be neglected.

Remark 4. The platform is operated directly from a Matlab/Simulink interface. By using this there is practically no limitation in the type of controllers that can be implemented.

3. APPLICATIONS

This section describes some of the actual and possible applications of the INOVE testbed. Such application are presented in three topics: modelling, observation and estimation, and control and fault tolerant control.

3.1 Modelling

3.1.1 Dynamic model of the vehicle

The test bench allow to model the vertical dynamics of the vehicle for control or estimation purposes in the following configurations:

- Quarter of Vehicle (QoV): This 2 DOF model allows to study the vertical behaviour of a vehicle in a corner. This model consist of the sprung mass (which models the body) and an unsprung mass (which models the wheel and suspension elements), connected each other by a spring, modelled by a stiffness and a damper. The unsprung mass is linked to the ground with the tire, modelled by a stiffness.
- Half Vehicle: The model is an extension of the QoV model which considers 2 additional DOF. The model is made up by a sprung mass with vertical translation and rotation in one axis (pitch or roll) and two unsprung masses.
- Full Vehicle: This is 7 DOF model considers all the vehicle vertical dynamics: wheels vertical dynamics, heave, pitch and roll. This model is made up with a sprung mass with vertical translation and rotating on two axes, and the four unsprung masses, each one in vertical translation.

As an example of dynamic modelling in the scaled vehicle, Fig. 3 shows a comparison of the *QoV* model and the experimental data.

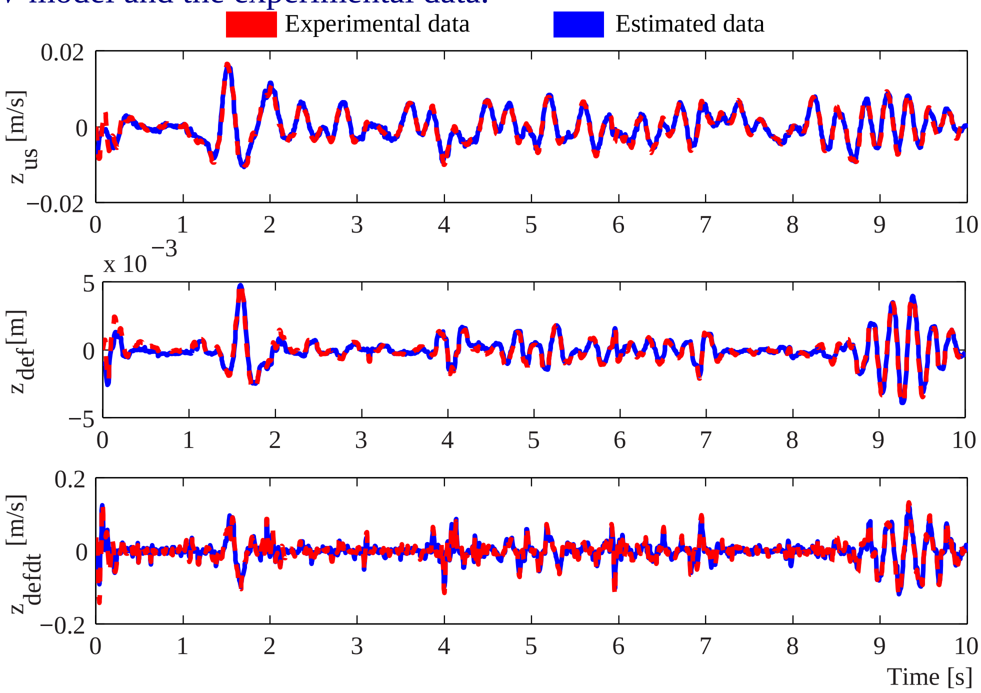

Fig. 3 Comparison of the QoV model and experimental data.

3.1.2 Electro-Rheological damper model

A reliable *ER* damper model is needed for the design/evaluation of a suspension control system, this test-bench allows the implementation of the Design of Experiments (*DoE*) for *ER* dampers modelling. Different kind of models are available for modeling the *ER* dampers, they can be classified as parametric and non-parametric models. Among the parametric models the most representative model structures are the Bingham model [3], the phenomenological and semi-phenomenological models [4, 5], the Bounc-Wen model [6], the inverse tangent function model [7] and the hyperbolic tangent function model [8]. Many of these models use parameters of the internal structure of the shock absorber.

In the non-parametric models, the coefficients do not have a physical meaning. Polynomial models [9], models based on Fuzzy Logic [10] and Artificial Neural Networks are the most representative frameworks.

As an example of modelling of the testbed *ER* dampers, a *DoE* based on [11] was implemented to identify the parameters of the Bingham model and the hyperbolic tangent function model. Fig. 4 shows the comparison between the estimated and the experimental force for the left-rear damper in the Force-Velocity (*FV*) diagram.

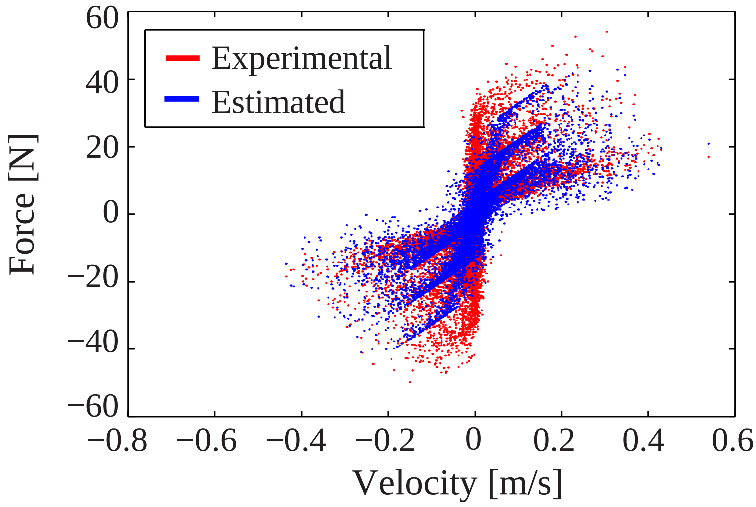

Fig. 4 Experimental and hyperbolic tangent model *FV* diagram of the left-rear damper.

3.1.3 Multibody model

A multibody model of the testbed can be obtained in order to study the dynamic behaviour of the vehicle components. This kind of model allows to analyse how loads and forces are distributed throughout the mechanical system.

3.2 Observation and estimation

3.2.1 State variables observation

Many suspension control strategies assume full state measurement or demand the use of several sensors. In addition, there are variables that cannot be directly measured, for instance the masses velocities. The estimation of the vehicle states is useful to reduce the number of sensors and the cost of the system. The main difficulties on the state estimation for suspension systems are the highly nonlinear behavior of the *ER* dampers and the influence of the road profile in the vehicle dynamics which may be considered as unknown.

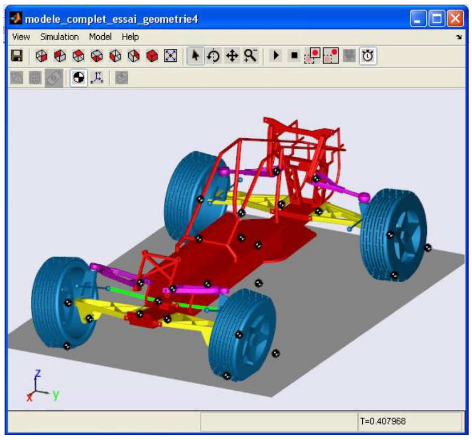

Fig. 5 Multibody model of the scaled vehicle in SimMechanics^{TM}.

In [12] two observers based on the *QoV* model were presented to estimate the vertical velocities of the scaled vehicle. Since the exact decoupling of the road profile is not possible due to non-detectability, an approximated Unknown Input Observer (*UIO*) and a robust H_∞ observer were designed. The experimental results showed that both approaches were able to produce acceptable estimations in nominal conditions; the H_∞ observer was less sensitive to sprung-mass uncertainty whereas the *UIO* had better accelerometer noise rejection property. Fig. 6 show the estimated sprung mass velocity with both observers in these two scenarios.

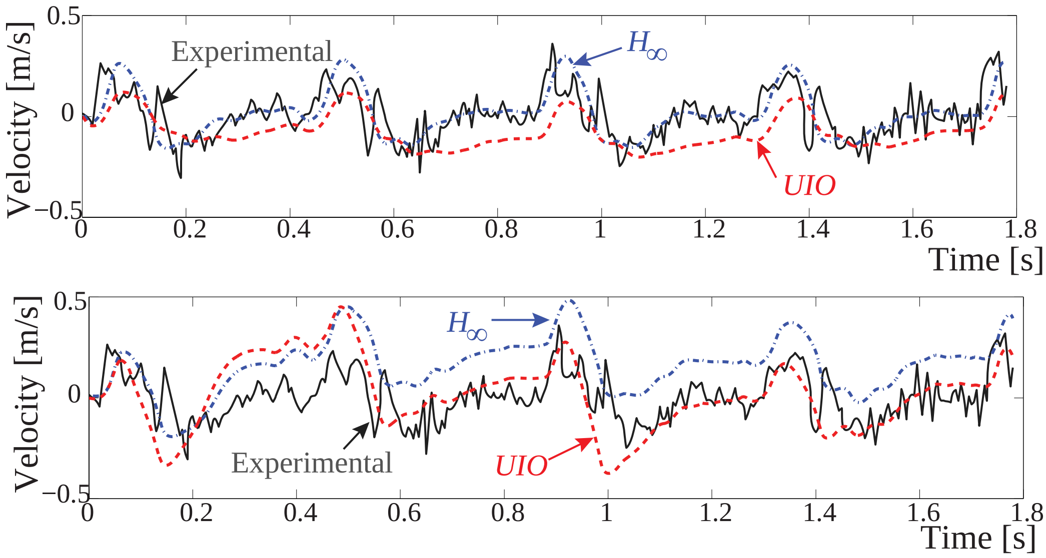

Fig. 6 Estimated sprung mass velocity in the five bumps test considering sprung mass uncertainty (top) and low frequency noise in acceleration measurements (bottom).

For a full vertical car observer, the methodology proposed in [13] can be applied.

3.2.2 Road profile estimation

Since the vehicle dynamics depend on tire-road contact forces, the road profile is one of the most important factors that determine the vehicle performance. Therefore, the knowledge of the road profile can be used to adapt the semi-active suspension features. The direct measurement of the road represent an expensive solutions, thus the estimation methods with low cost instrumentation have gained importance. In [14] a novel road profile estimation method based on a H∞ robust observer was proposed to online compute the road roughness. An alternative method based on the Q-parametrization was proposed in [15]. Unlike the H∞ robust observer, this method does not require a vehicle model. The Power Spectral Density (*PSD*) function is then used to characterize a road in the frequency domain. By using the limits of roughness for each type of road defined by the ISO 8608, it is possible to identify the road profile on which the vehicle is driven. This information is used to adapt the suspension damping according to the road type. Both approaches were experimentally validated in the vehicle platform. As illustration, Fig. 7 shows the estimated road profile using the H∞ observer.

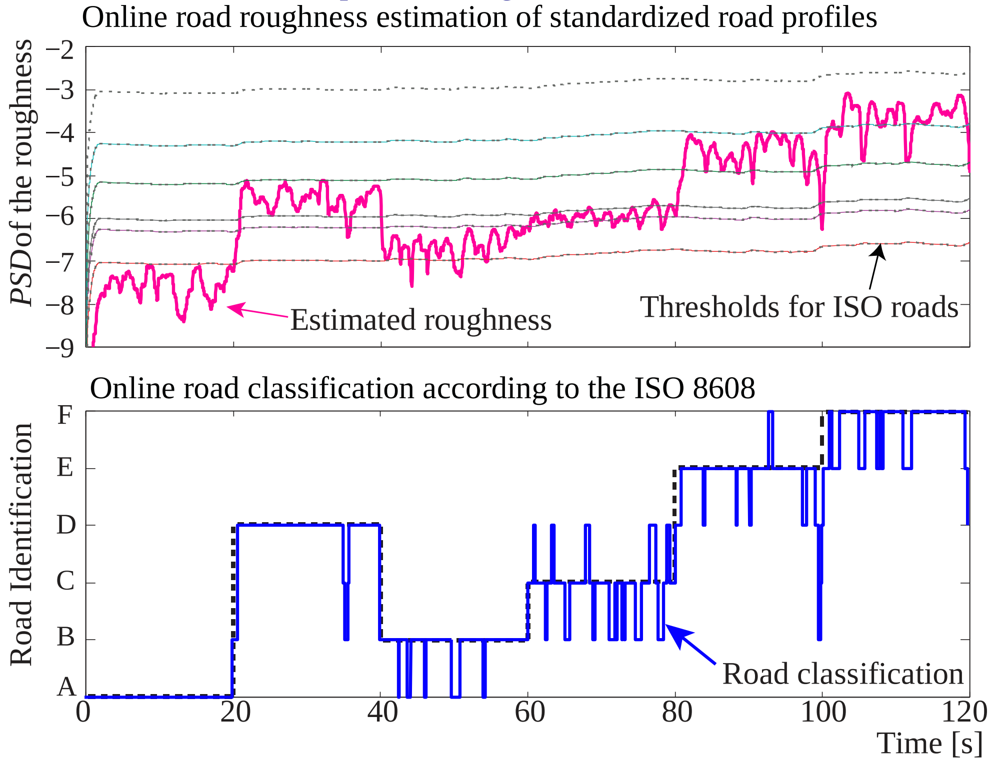

Fig. 7 Online roughness estimation and classification using the H∞ observer.

3.2.3 Fault Detection and Isolation

Vehicle manufacturers have been gradually increasing the number of control systems to improve the vehicle safety and performance. The increased complexity of the systems introduce the need of fault detection and fault tolerant control. In general, two type of faults can occur, sensor faults and actuator faults.

The typical instrumentation of a semi-active suspension system includes accelerometers, deflection sensors and rarely force sensors. A sensor failure can occur as a gain deviation, bias, breakdown or offset. Party space and observers are the classical methods to deal with this type of faults [16]. Due to the instrumentation of the testbed, several configurations of *FDI* modules can be implemented to detect single or multiple sensor faults.

On the other hand, oil leakage is the most common actuator fault in the semi-active suspension system [17]. Among the potential causes of faults are: worn out seals, misalignments in the attachment points, piston rod damages during installation, manufacturing defects and overheating. For uncertain systems such as the vehicle model, the classical parity space method has drawbacks to create a perfect null space between uncertainties and outputs. An approach to add robustness to the parity space method inspired on [18] was used to design residues to detect actuator faults. The approach was formulated as a min/max optimization problem. Fig. 8 shows the estimation of the faulty force in the scaled vehicle. Other data driven approaches, like the transmissibility function [19] can also be used to detect damper faults.

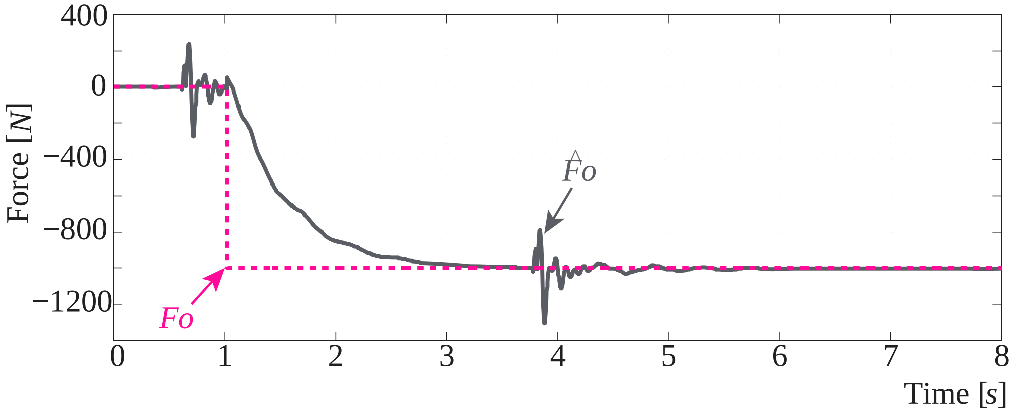

Fig. 8 Actuator fault estimation with the robust FDI module based on parity space.

3.3 Control and fault tolerant control

By adjusting the mechanical characteristics of the suspension system, the vertical movements of a vehicle can be modified. In traditional suspension systems (passive) this tuning is fixed and has to be oriented according to the purpose of the vehicle. Semi-active suspensions are able to modify this setting using a semi-active shock absorber. This adjustment requires the implementation a control system to manage the desire objective (comfort or road-holding) [20]. Such control systems can be designed to operate only in one QoV or in the complete suspension, also this systems can be tolerant to faults that can occur in the vehicle.

The INOVE test bench is equipped with four ER dampers, which can be using a wide variety of control techniques. Because the interface of the testbed is implemented using Matlab/Simulink, there is practically no limitation in the type of controllers that can be implemented in the system. Fig. 9 shows the distribution of the variables and possible imputes on the control system of the INOVE test rig.

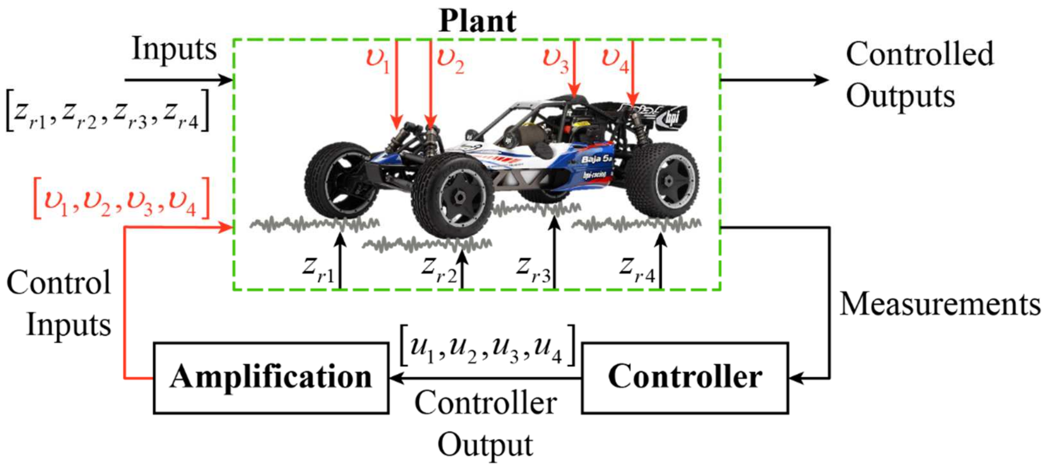

Fig. 9 Schematic of the control system of the INOVE testbed

3.3.1 QoV oriented control algorithms

The classical approaches to control a semi-active suspension are the On/Off algorithms. This approaches are designed to operate in a QoV, the most known are Sky Hook (SH), Ground Hook (GH) and Acceleration Driven Damping (ADD). This algorithms select between two values of damping coefficient, usually maximum and minimum, using measurements from the QoV. Fig. 10 shows the results of the implementation of this algorithms in the rear left corner of the SOBEN car, the figure on the left is related to comfort performance of the algorithms and the figure on the right are related to road-holding.

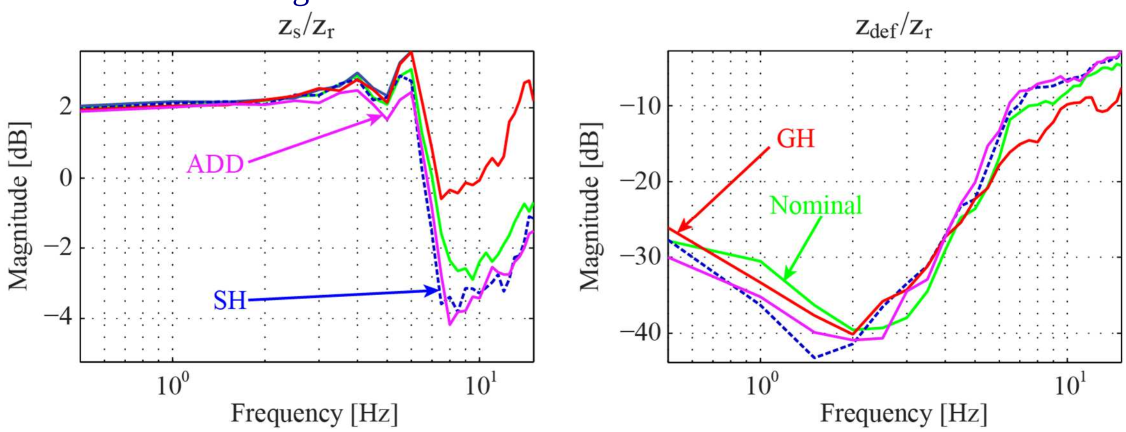

Fig. 10 Frequency responses of different control algorithms, for comfort (left) and road-holding (right).

3.3.2 Full suspension oriented control algorithms

Another approach regarding On/Off controllers, but this time designed to manage the full suspension system simultaneously, is presented in [21]. This control technique, in an offline analysis, evaluates the performance of each possible combination with respect to a certain frequency range, and using the optimization index of [22], the controller selects the best combination for each frequency. After in an online procedure the algorithm calculates the current frequency of excitation and set the corresponding damper combination. The results of this controller are shown in Fig. 11, where the red line is the worst possible performance for each variable, the green represents the best possible performance achievable. The gray area is the valid actuation region and the blue line is the actual performance considering all the variables of interest.

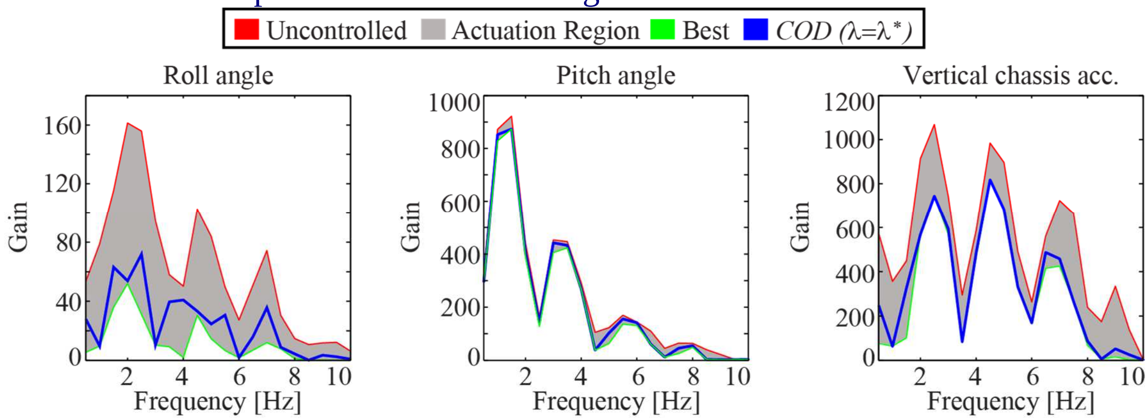

Fig. 11 Results of the COD controller for comfort oriented variables.

3.3.3 Fault Tolerant control strategies

Since this systems are susceptible to suffer from different faults, in [23] a fault tolerant control strategy is presented. This strategy detects if the damper have lost some of its force dissipation ability and adjust the manipulation to that damper to overcome the lost. Fig. 12 presents the results of the proposed strategy regarding the induced roll angle due to the fault.

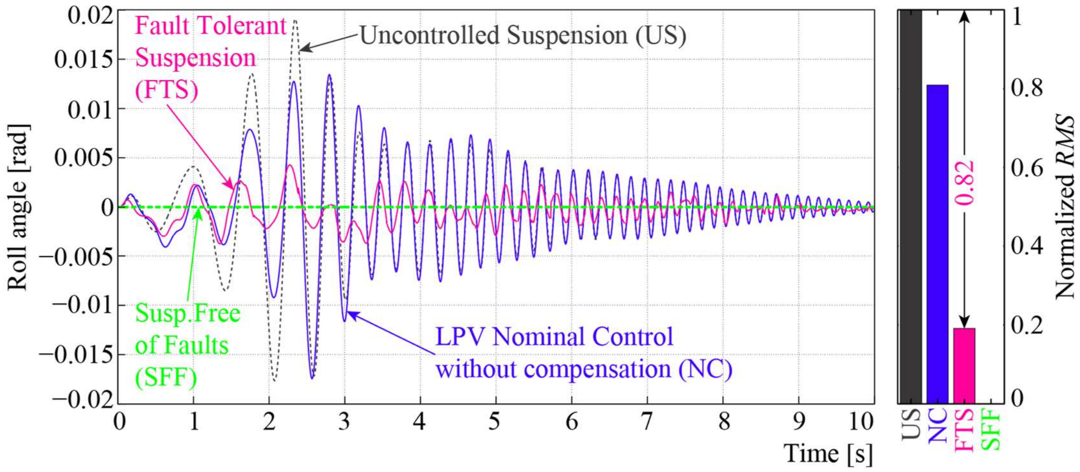

Fig. 12 Results for the fault tolerant controller strategy

4. CONCLUSIONS AND FUTURE WORK

This work has presented some of the developments that have been done using the INOVE experimental platform. These implementatios have proven the effectiveness of the testbed and its capabilities to implement different estimation ans control schemes.

The current efforts in this platform are focused on the implementation of robust approaches like H∞ and LVP control techniques as well as full vehicle control schemes. In addition, the INOVE testbed can be used for research and teaching purposes. In this sense, it serves as a platform to validate estimation and control approaches and evaluate its implementation issues.

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